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STATUS OF FLIGHT LEAK MEASURING TRANSDUCERS

By

C. T. N. Paludan

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INSTRUMENTATION DEVELOPMENT BRANCH
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Huntsville, Alabama

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ABSTRACT

21915

Transducers capable of measuring small flow rates resulting from leaks in flanges in the Saturn engine systems are being developed. Principles of operation of three basic types are given in detail. The inhouse environmental tests were satisfactory; operational tests are now being made at Rocketdyne.

Leakage rates up to 1000 standard cubic centimeters per minute may be measured with the present units. These units are specifically designed for liquid oxygen leaks, but are also inherently capable of operation with other cryogenic liquids, gases at less than 100°C, or even hot gases.

Operational units of one type are considered to be available for inflight use. Some additional development work is required on the other two types. Considerable further work is required to adapt units for use with liquid leaks.

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STATUS OF FLIGHT LEAK MEASURING TRANSDUCERS

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SUMMARY

Three basic types of sensitive flowmeters suitable for monitoring leakage from engine flanges during Saturn flights are being developed. A special dual seal in the flange made the collection of these leaks possible. Details of the seal and each of the three instruments are given. Satisfactory prototypes of all types have been built and are presently undergoing tests on the J-2 engine at Rocketdyne. Thirty additional transducers are expected to be delivered in August 1962. Present transducers are specifically designed for lox or gox leaks; they can be used for leaks of any cryogenic liquid or any gas of temperature less than 100°C. With minor modifications, they can be adapted to hot gas leaks; measurement of liquid leaks will require considerable additional development.

INTRODUCTION

While development of transducers for inflight leak detection has been proceeding within Astrionics Division since 1959, the basic ground rules under which the current program operates were established on April 6, 1961*. Basic requirements were:

Range: 10 to 1000 standard cc/minute flow rate
Accuracy: ±20% F.S. required, better desired
Curve: One range, greatest sensitivity at low end preferred
Medium: Lox and hot gas leaks most critical
Connection: Standard 1/4 or 1/8 inch tubing fitting on flange
Funding: M-ASTR as part of Saturn project.

A previous status report was given on February 23, 1961[1]. Arrangements have been made for testing of prototype transducers by NAA Rocketdyne during static tests of the J-2[2] and F-1[3] engines. This testing was made possible by the Rocketdyne Naflex dual seal**.

This status report is in answer to a request for additional information by Saturn S-II and S-IV B stage contractors***.

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* Meeting held April 6, 1961, in Mr. Paul's office between personnel from Astrionics, Test, and Propulsion & Vehicle Engineering Divisions.

**Meeting held November 16, 1961, in M-P&VE conference room between personnel of Rocketdyne and representatives of Astrionics, Test, and P&VE Divisions.

*** Meeting held on May 22, 1962, at Rocketdyne, Canoga Park, Calif., "J-2 Engine - Stage Interface Meeting," between MSFC, Rocketdyne, NAA-S&ID, Douglas, and others.

TYPES UNDER STUDY

A leak transducer is essentially a flowmeter for small rates. Several types have been investigated and dropped from further study at this time. These include turbine flowmeters, heated thermistor anemometers, vortex tube Δt devices, conventional Δp transducers, and strain gage flexleaf devices.

Three basic types of transducers are currently considered to meet the basic requirements. These are the Trans-Sonics Equibar Δp transducer, the Fenwal-type hot wire anemometer, and the Hastings-type hot thermocouple anemometer.

The Δp unit is being developed under the supervision of Mr. W. T. Escue, M-ASTR-IM (project formerly supervised by Mr. O. L. Smith). The hot element anemometers are being developed under the supervision of Mr. H. D. Burke, M-ASTR-IM. All are designed for lox leaks. It is expected that they can be used with any gas leaks, including hot ~~gages,~~ gases and any cryogenic liquid leaks. However, they will not work with liquids without modifications.

The hot wire instruments measure mass flow rate, while the Δp instrument measures volume flow rate. All instruments built to date have a full scale range of 0 (or 10) to 1000 standard cc/minute of oxygen (0 to 1429 milligrams/minute O_2). All prototype units have successfully passed the vibration and temperature environmental tests as specified for the thrust frame area[4].

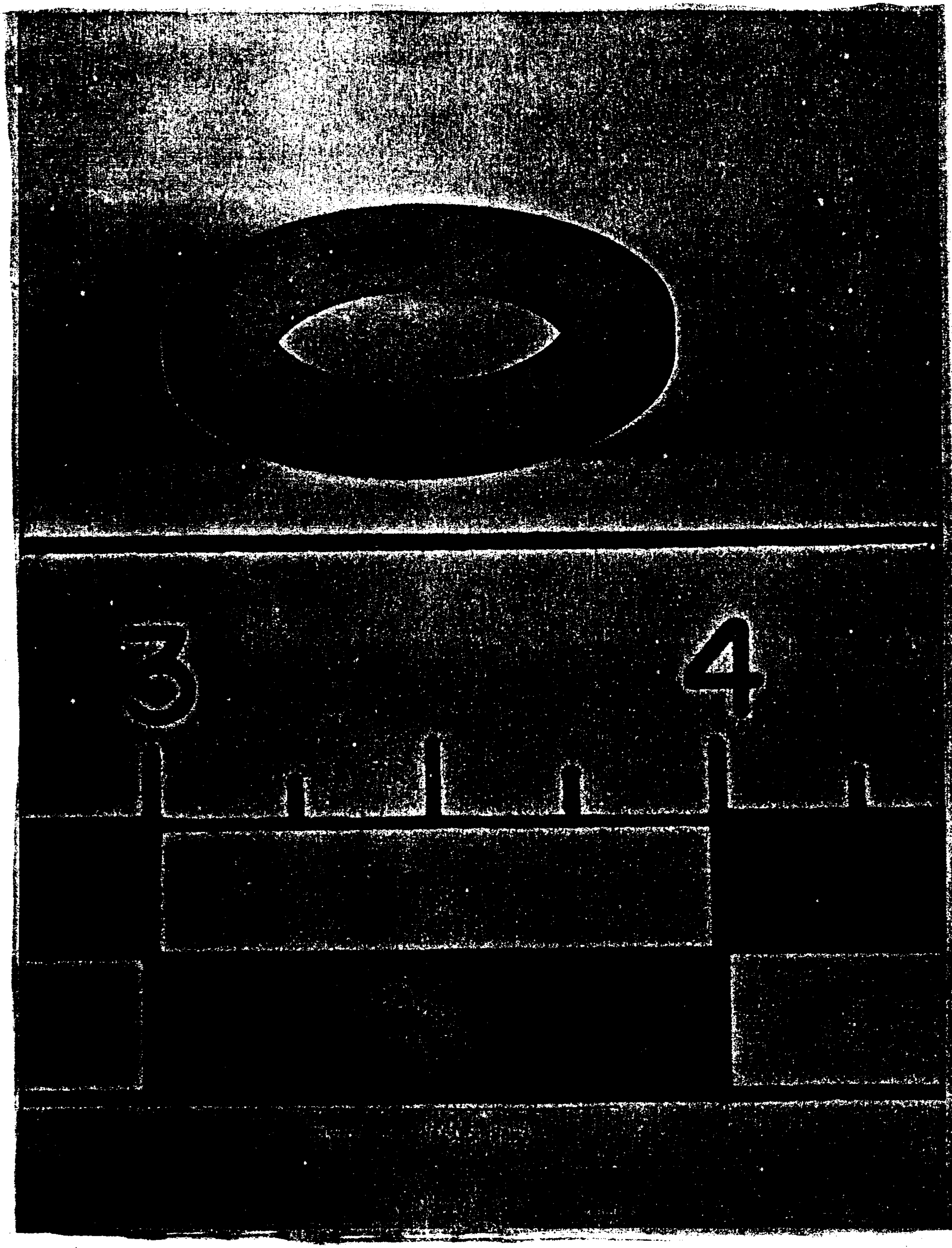
PRINCIPLES OF OPERATION

Naflex* Dual Seal

Since the transducers under discussion are discrete instruments, not area-surveillance devices, it is necessary that potential leaks be collected and routed to them. There are several possible methods of accomplishing this. A flexible or rigid "boot" could be installed around joints or flanges of interest. Several arrangements of two seals are possible; however, all of these are somewhat awkward or inadequate. Rocketdyne has developed a highly reliable seal and has combined it with a second seal in one gasket which provides a very convenient leak detection capability[5]. Their primary seal has the trade name "Naflex."

Figures 1 and 2 show two Naflex gaskets with dual seals. Figure 3 is an idealized sketch of a typical installation. It can be seen that the primary seal for high pressure is accomplished by the teflon-coated lip of the inner-most radius of the metal gasket. Between the primary seal and the secondary seal (which is of the nature of a flat gasket), a cavity

*Trademark, North American Aviation, Inc.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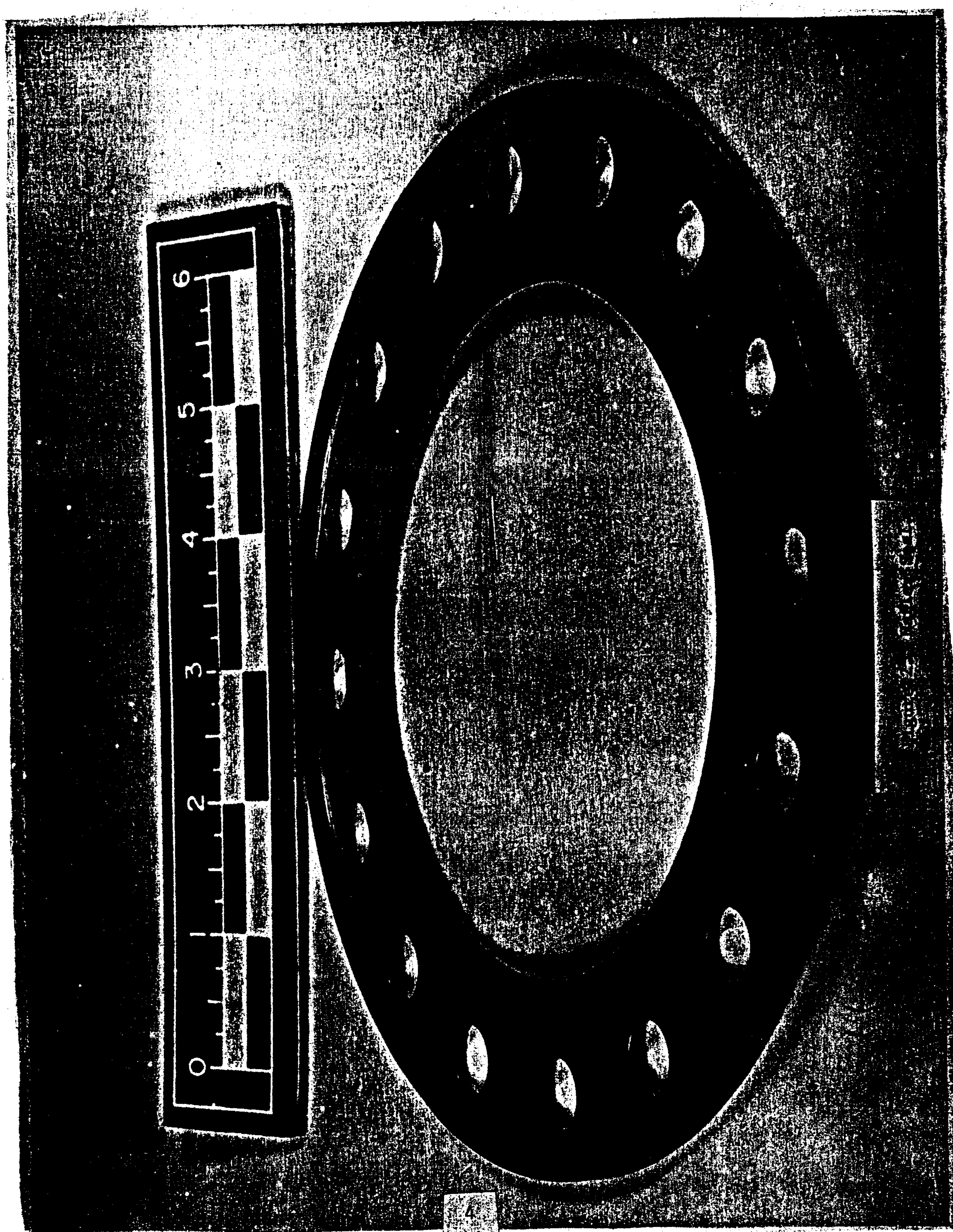

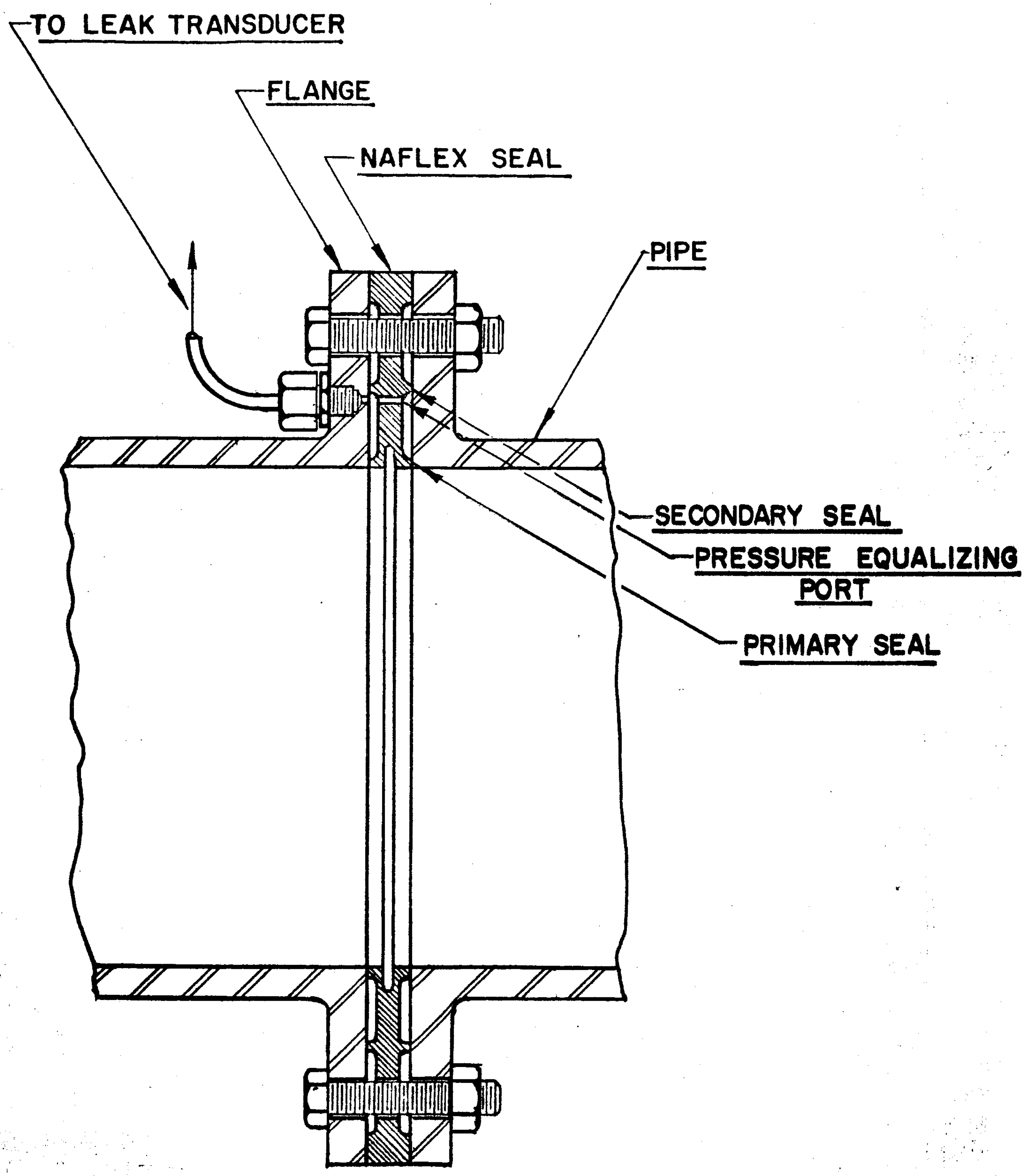

Figure 3. Typical Flange with Naflex Seal.

exists within which primary seal leaks would collect. A port into this cavity permits venting of the leak gases (or liquids) to the leak detecting flowmeter via a 1/8-inch tube.

Rocketdyne is including Naflex dual seals in certain flanges on the J-2 and F-1 engines. They have also developed an analogous secondary seal for flared tubing fittings.

It is anticipated that some non-engine joints within the vehicles will be provided with dual seals for leak detection.

Differential Pressure Instrument

Pressure drop in a capillary tube is a function of the flow rate through it. Measurement of this by means of a differential pressure transducer will therefore yield flow rate information. Prototype transducers using this principle have been built by Trans-Sonics, Inc., Burlington, Massachusetts, under Contract No. NAS8-1699.

This instrument is based on Trans-Sonics' high sensitivity Equibar* differential capacitance pressure transducer. The transducer employed in this design is a low force type. Two gold-plated glass discs positioned on both sides of a stretched diaphragm form a pressure sensitive differential capacitor. The diaphragm is stretched and held in tension by a pair of clamping rings. The glass discs are positioned and held in place by a pair of belville springs. As pressure is applied to one side, the diaphragm is deflected causing the capacity to increase on one side and decrease on the other. The Equibar is used as part of an a.c. bridge circuit; therefore, an unbalanced condition produces an output signal that is proportional to the phase and magnitude of the input pressure. The pressure sensitivity is determined by the characteristics of the stretched diaphragm. The leak detector Equibar is designed for a full scale sensitivity of 30 mmHg.

Trans-Sonics has derived and empirically corrected a formula for the volume flow rate**.

$$Q_s = 976\left(\frac{P_1}{P_s} + .024\right)\left(\frac{T_s}{T_1}\right)^{.72}$$

where Q_s = volume flow rate in cc/second at standard pressure of 760 mmHg (P_s) and standard temperature of 298°K(T_s). P_1 is the pressure at the tube's outlet in mmHg, and T_1 is the gas temperature in the tube in °K.

It can be seen that the flow rate is a function of ambient pressure and gas temperature. The calibration curve must therefore be corrected

*Trademark, Trans-Sonics, Inc.
**See Appendix A.

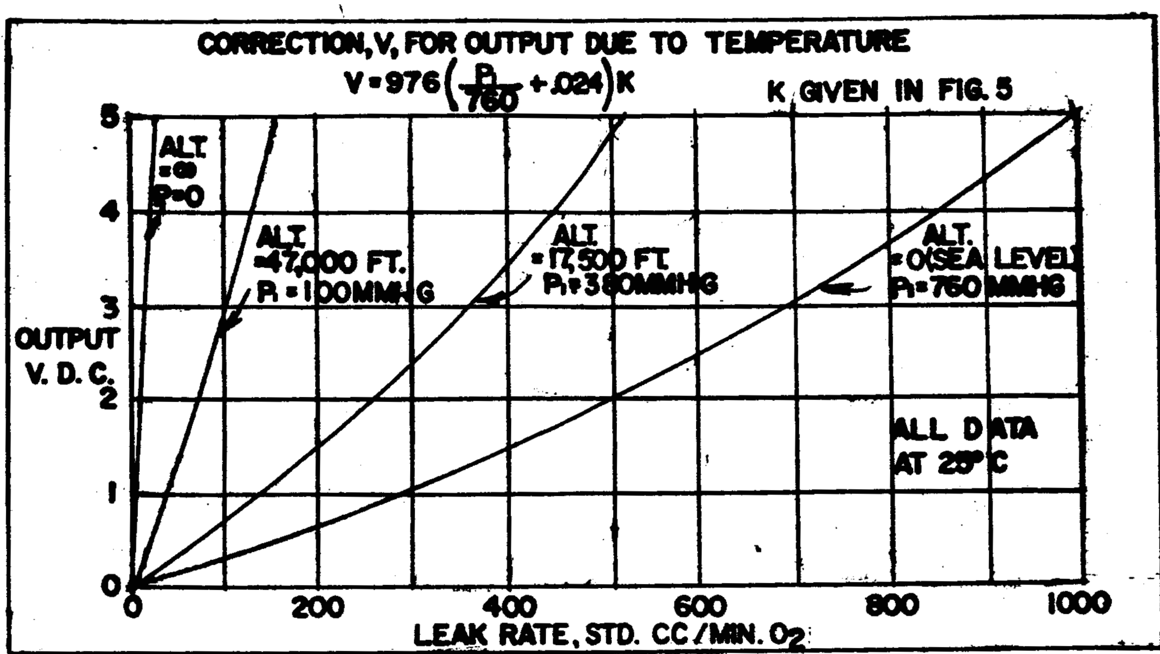

Figure 4. Calibration Curves, Δp Transducer.

for altitude and temperature. Figure 4 is a family of curves of output versus flowrate at several altitudes. Figure 5 is the temperature correction for a typical transducer.

The electronic design consists of an oscillator, bridge circuitry, emitter follower, and phase detector circuits. These circuits are designed for operation over the full temperature range of -100 to +200°F

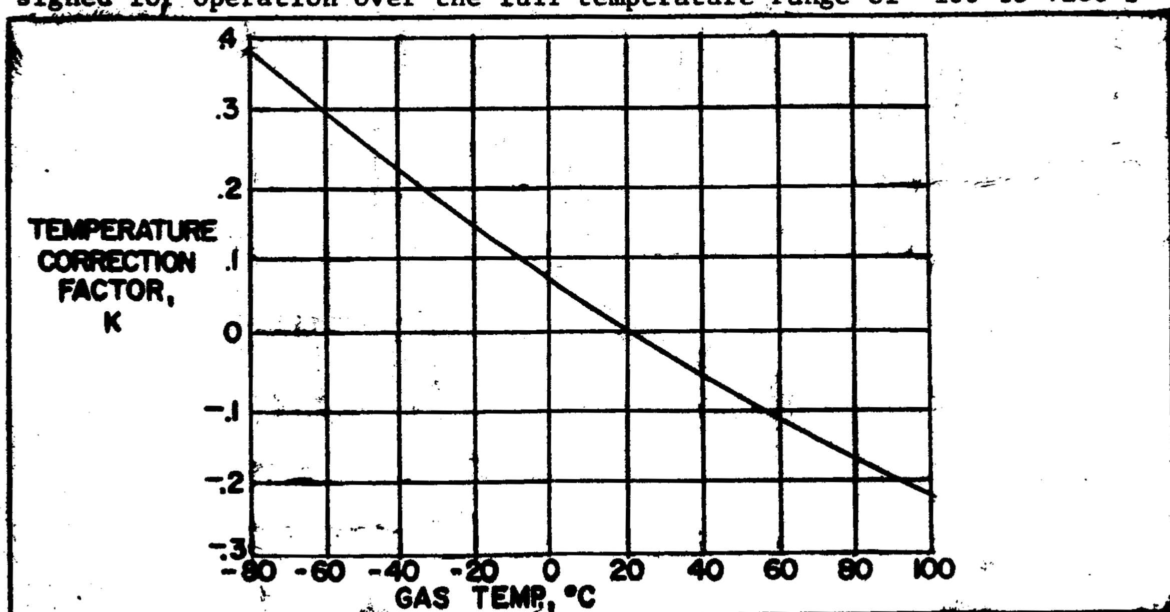

Figure 5. Temperature Correction Curve, Δp Transducer.

Figure 6. Δp Transducer.

(-73 to +93°C). An internal heater will go on at temperatures below +40°F (+4°C). The purpose of the heater is to prevent moisture condensation inside the pressure transducer. A relay is included to permit insertion of a test signal for automatic checkout and for final adjustments. The transducer operates from unregulated 28 v d.c. The output impedance is approximately 3,000 ohms. The first prototype is shown in Figure 6.

Heated Thermocouple Anemometer

The cooling effect of gas (or liquid) flow on a heated thermocouple element is the basis for this transducer. For many years a device of this nature has been available from Hastings-Raydist, Inc., Hampton, Virginia. It is not satisfactory for flight use without modification, however. At present, two companies are developing modifications: Space Craft, Inc., Memorial Parkway, Huntsville, Alabama, Contract No. NAS8-2610 and Radiation Technology, Inc., 715 Miami Circle, N. E., Atlanta 5, Georgia, Contract No. NAS8-2629.

The Space Craft prototype is shown in Figure 7. Not shown is a standard d.c. amplifier module which is also required. (The d.c. amplifier is identical to that used for temperature measurements.) The Radiation Technology unit will also require the d.c. amplifier. A prototype of this unit is shown in Figure 8. The d.c. amplifier module will provide relays for automatic checkout.

A circuit diagram of the heated thermocouple unit is shown in Figure 9. The thermocouple detector is heated producing a millivolt emf of some calculated value. This emf is biased by an equal but opposite polarity emf delivered by the bridge network in the signal conditioning module. The bias emf is constant once it is set in the lab. As a leak begins, it is channeled across the heated thermocouples, reducing their temperatures and the emf from the detector. The difference in emf between the detector and the bias is fed into the amplifier and provides the 0-5 v d.c. signal for telemetry.

Thermocouple heating is by I^2R power dissipation and, since one requirement was low power consumption, a high resistance thermocouple was desired. Also desired was a thermocouple with high emf at relatively low temperatures (under 200°C). A thermocouple made of chromel/constantan satisfied both of these requirements in that it has an average of 10 ohms/ft higher resistance value than chromel/alumel and almost twice the emf output at the same temperature.

Vehicle power available necessitated the use of 115 v a.c., 400 cps, for efficient heating of the thermocouples. Step-down transformers are used to supply approximately 1 volt to the thermocouples. A voltage adjustment is provided in the primary circuit to control the heating power

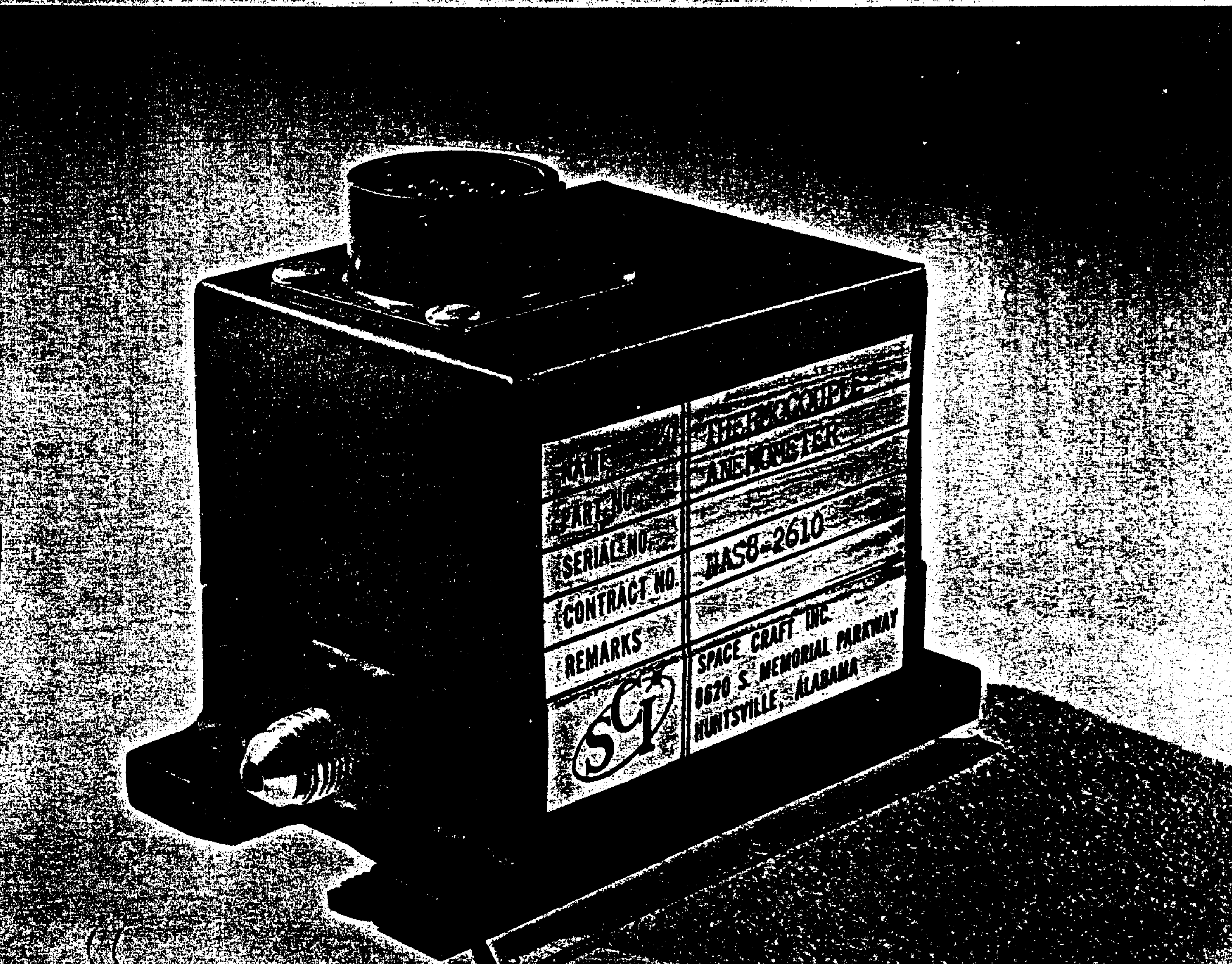

Figure [illegible] Thermocouple Anemometer

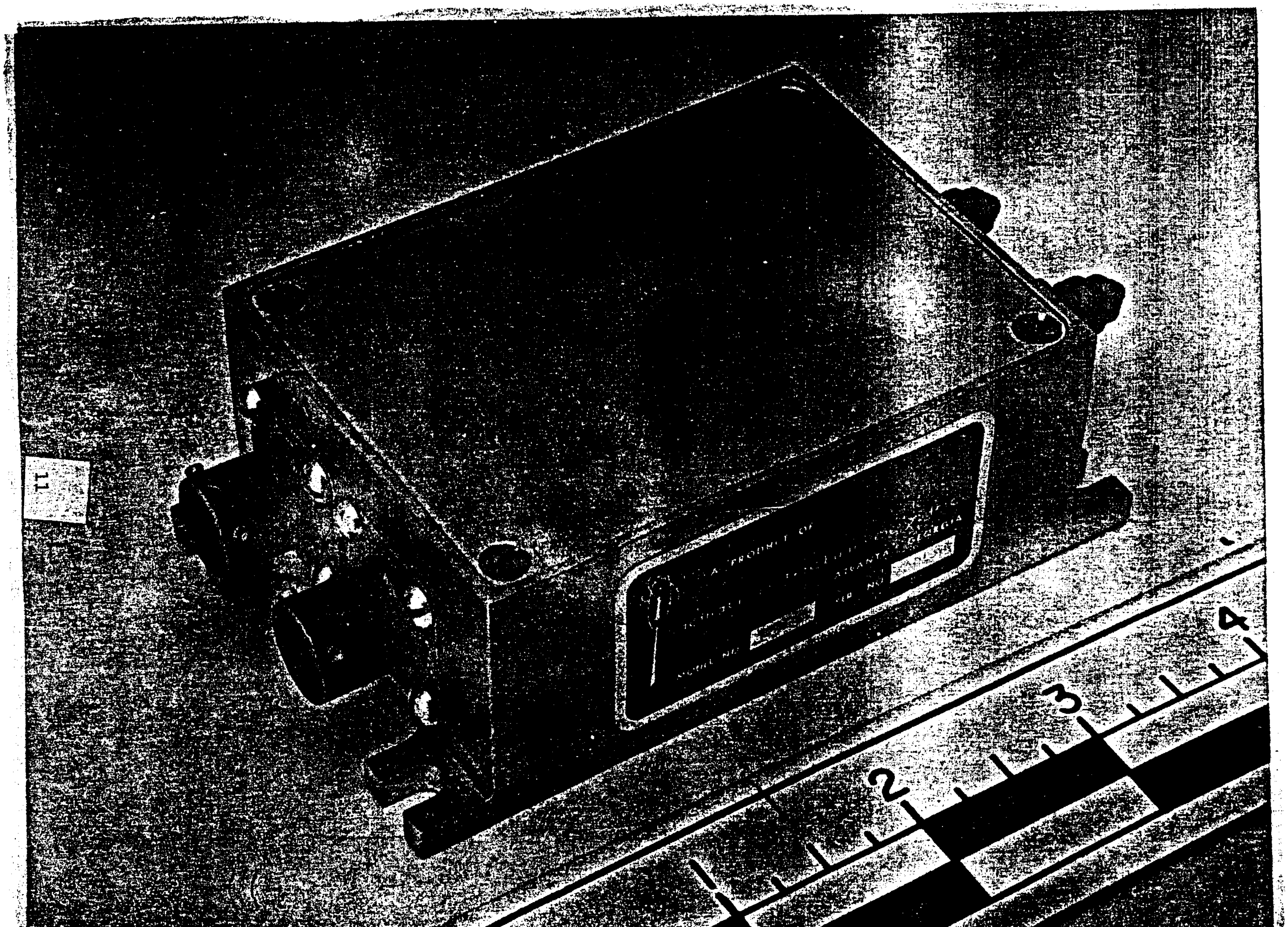

Figure 8.- Heated Thermocouple Anemometer.

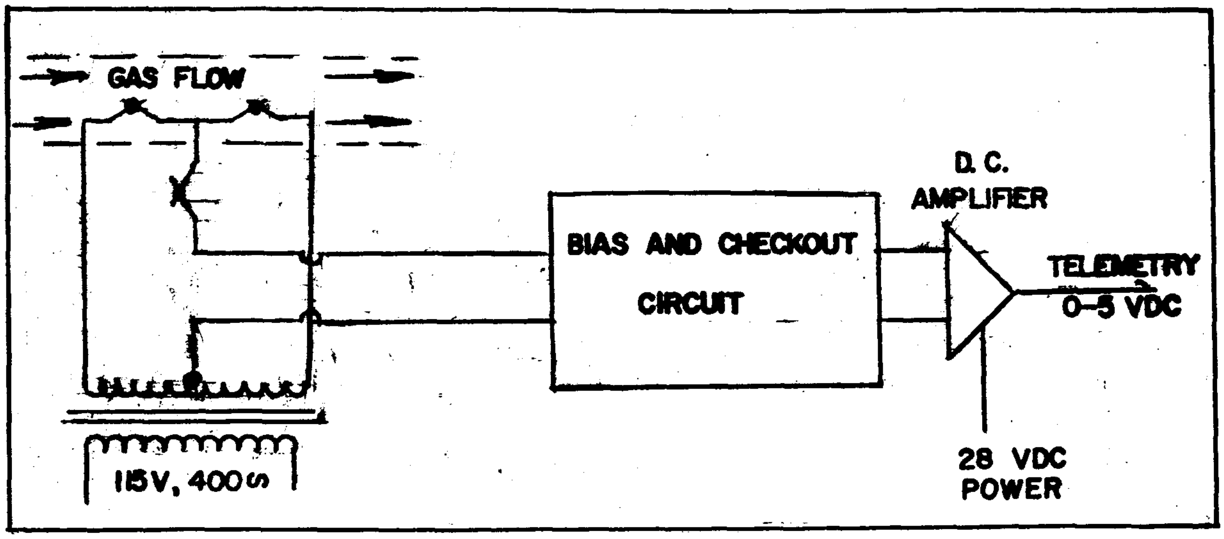

Figure 9. Circuit Diagram, Heated Thermocouple Unit.

supplied to the thermocouples. The voltage adjustment also serves as a sensitivity control in that the more heat on the thermocouples, the more sensitive they will be at the lower flow rates. Use of a.c. power and a transformer required two thermocouples in parallel since current flow is supplied through the transformer. In this arrangement, it can be seen that on one cycle the thermocouple current is in opposition to the transformer current and on the next cycle they are in phase. Across the center tap of the transformer and the reference junction, the emf from just one thermocouple is impressed on one cycle and the emf from the second thermocouple on the next cycle. This forms an essentially constant d.c. voltage with some ripple present. A filter is necessary because the half-cycle resistances are not exactly equal.

The reference junction also serves as compensation for changes in ambient temperature of the leaking gas or the housing assembly as it is subjected to the same ambient temperatures as the heated junction. The reference junction is physically located in essentially stagnant gas so that it is sensitive only to changes in gas temperature.

The thermocouples have maximum output when the flow rate is zero and minimum output when the flow rate is at a maximum. To obtain a 5 mv differential emf from the thermocouples, it is necessary to heat them to approximately 180°C. The thermocouple emf is filtered and then fed in series with the opposite polarity of the bias voltage. The input to the amplifier is then zero under no flow conditions. When a flow is passed over the thermocouples, reducing their emf, the unbalance is fed into the amplifier and a proportional voltage is seen as an output signal. The bridge bias network is mounted on a printed circuit card inside the amplifier and has a variable resistor in one leg which is used in setting the zero output for no flow conditions.

A typical calibration curve is shown in Figure 10. It has the desirable characteristic of having the greatest sensitivity at low flow rates.

Although the transducer contains provisions for temperature compensation, the severe problem of cold oxygen (-170°C to -150°C in the vicinity of the flange) is met by using at least 1 to 2 feet of tubing to connect the transducer to the flange. A very high temperature gradient then exists. It is therefore possible to use a transducer compensated for ambient changes of ±20°C only.

Because of simple convective heat loss changes with changing altitude, compensation is required. Development of this compensation is progressing satisfactorily, so that one calibration curve will be usable without altitude corrections.

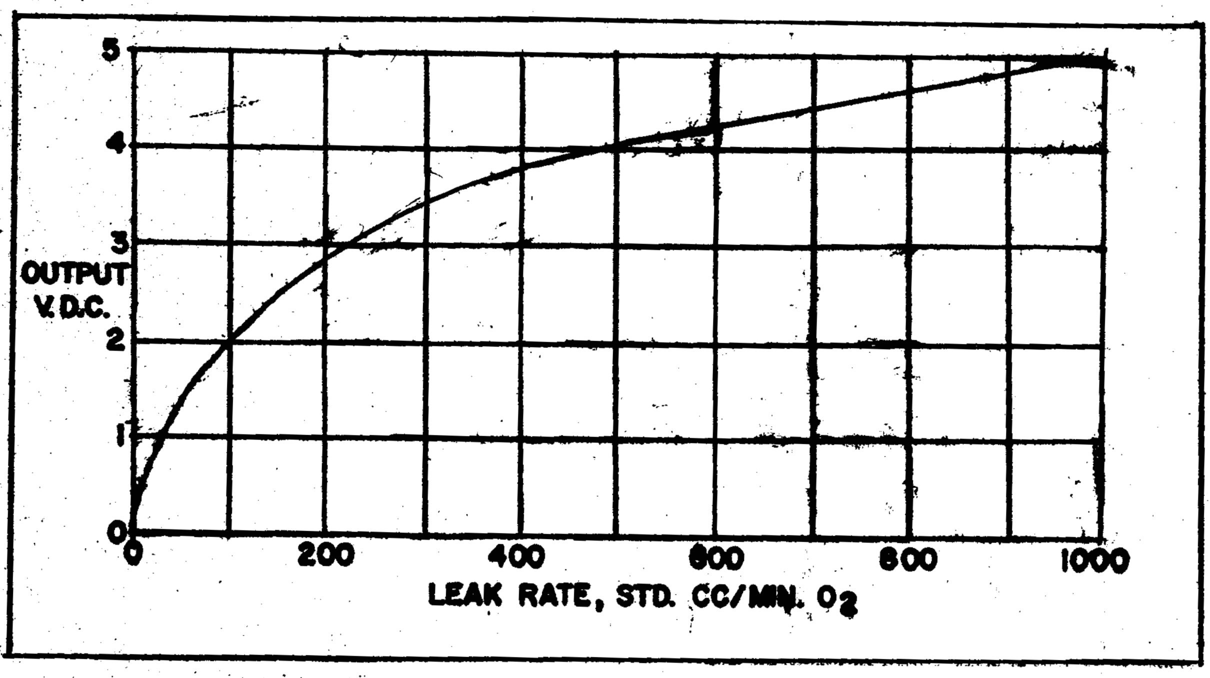

Figure 10. Calibration Curve, Heated Thermocouple Unit.

Hot Wire Anemometer

As in the heated thermocouple anemometer, the cooling effect of a flow stream on a heated element is the basis for the hot wire anemometer. Fenwal, Inc., Ashland, Massachusetts, has developed this instrument under Contract No. NAS8-2533. Development work on this unit is considered to be complete. A prototype transducer is shown in Figure 11. Not shown is the electronic circuitry, which is housed in a standard MSFC measuring module.

This unit is designed to meter the flow of oxygen from 10 - 1000 cc/minute (at 760 mmHg) at a gas input temperature from -183°C to +50°C. It will operate in an ambient temperature from -20°C to +30°C indefinitely and up to 80°C for a 5-minute period. All flow is heated (or cooled) to 30°C prior to sensing in the flowmeter. To precondition the gas flow to 30°C, a combination of an aluminum block heat sink and a block heating circuit is used. The block is heated by a uniformly distributed coil of wire and a solid state temperature controller utilizing a thermistor as the temperature sensor. A plastic foam material is used to thermally insulate the preconditioning block from ambient temperature.

A circuit diagram of the hot wire unit is shown in Figure 12. The flowmeter sensing element is a coil of resistance wire with a high temperature coefficient of resistance. This sensor is one leg of a Wheatstone bridge and under all flow conditions is maintained at a temperature some 25°C higher than that of the preconditioning block. The other bridge elements are two fixed resistors and one temperature sensitive resistor which is in thermal contact with the block to compensate for slight shifts in block temperature.

The cooling effect on the sensor element, because of a flow of gas, is detected as a change in the bridge output voltage. This output voltage change will determine how much additional heating power must be applied to the bridge to restore the bridge to near its balanced condition. It is a feature of this system that the reference condition be restored very rapidly, rather than allowing the bridge to remain unbalanced and using the error signal as an indication of a gas flow. If the latter were the case and the sensor were required to come to a new equilibrium temperature for each gas flow rate, the response time would be greatly lengthened. This is true because the outside of the sensing coil is embedded in a plastic foam sheath that would likewise have to come to thermal equilibrium.

To control the power supplied to the flowmeter, the present model has a servo amplifier. This amplifier has as its input the d.c. millivolt unbalance of the bridge circuit. Its output supplies the power to the bridge and also gives a 0-5 volt output signal to the telemetering circuit.

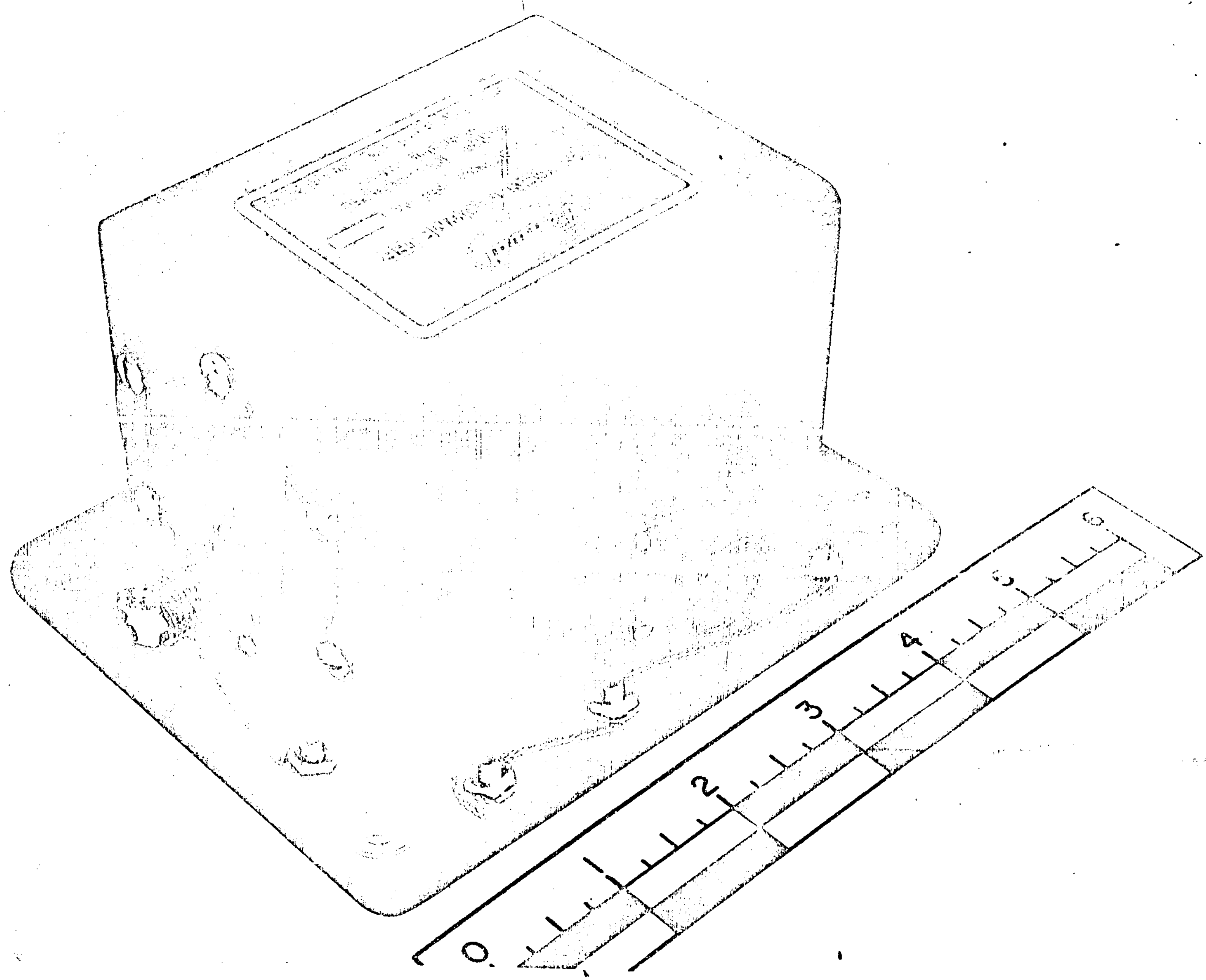

Figure 11. Hot Wire Anemometer.

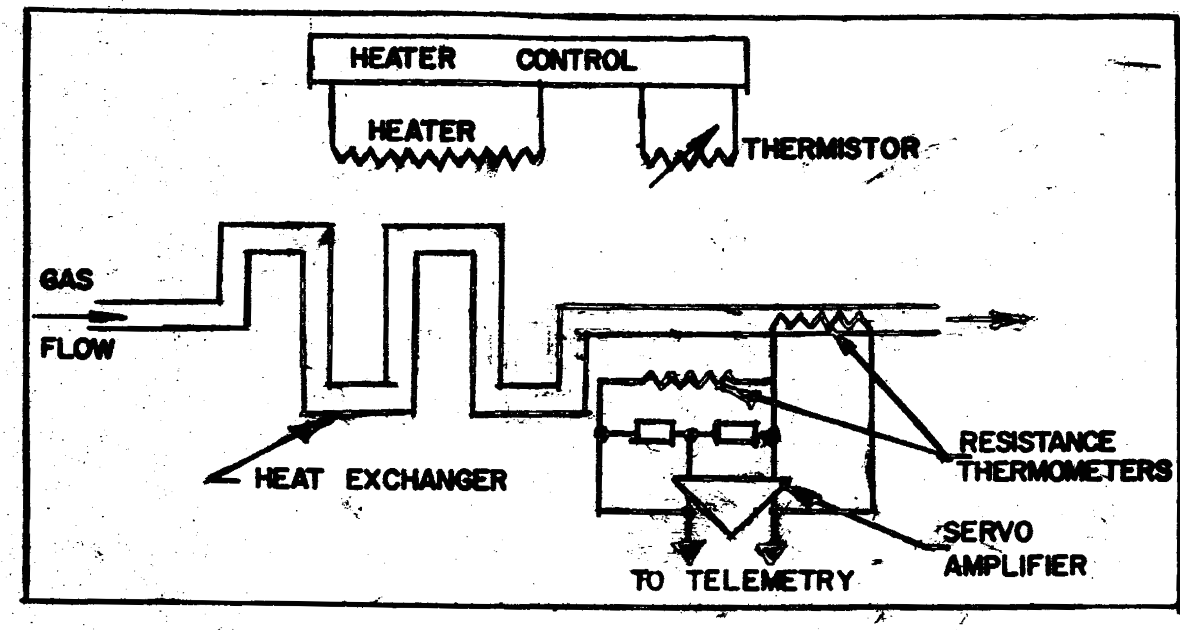

Figure 12. Circuit Diagram, Hot Wire Unit.

The amplifier circuit is in a separate enclosure from the flowmeter. It is in a standard module which will be located in the amplifier rack at a distance from the flowmeter.

The dimensions of the standard module and flowmeter are 3-1/2 x 4-1/2 x 1 inch and 3 x 3 x 3-3/4 inches, respectively.

The flowmeters have been tested to have a time response in the order of 0.5 seconds. This was done with a sudden air flow of 1000 cm/min. The 0.5-second response represents the time for the output to indicate 63% of this flow of 1000 cc/min. from a 0 cc/min. flow condition.

At this time, negotiations are being made to build another configuration of this system. This model is intended to have an a.c. servo amplifier for simplicity in that area. The present amplifier has the d.c. millivolt unbalance of the bridge as an input to a chopper and a.c. amplifier. The output of this is rectified and supplies the power to the bridge.

The block temperature is planned to be at a high temperature to accommodate a higher ambient temperature.

Another improvement will be to compensate the system so that it will give an accurate flow output reading at pressures down to 10^{-9} mmHg. Effects of altitude are not as severe on this unit as on the heated thermocouple unit.

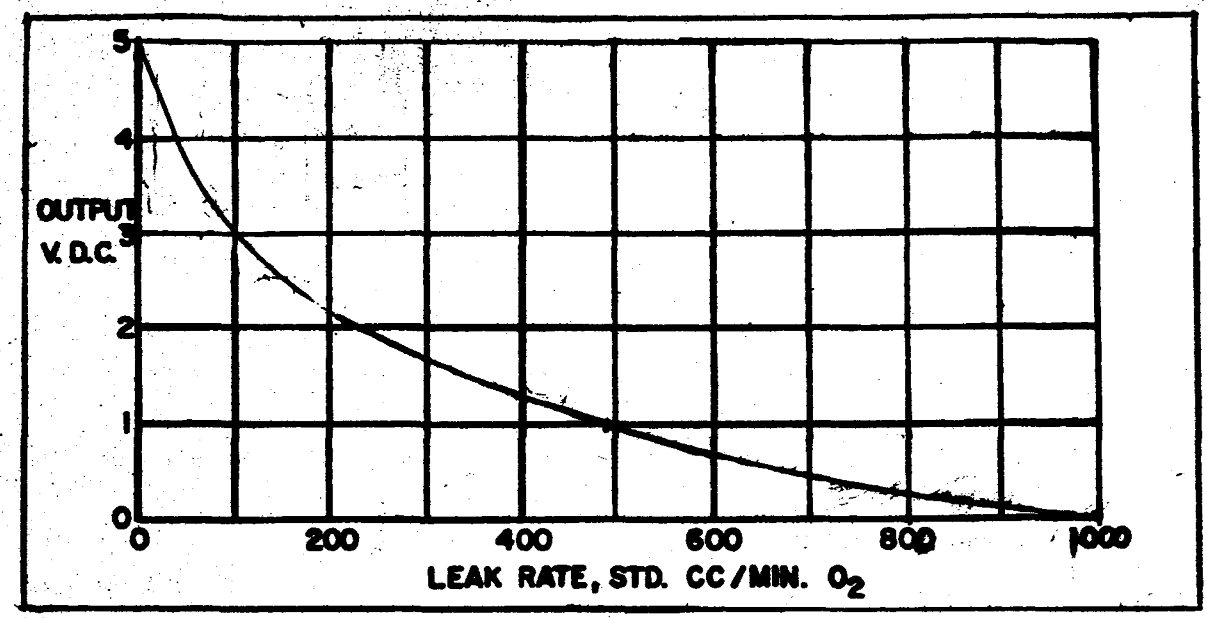

Figure 13. Calibration Curve, Hot Wire Unit.

A typical calibration curve is shown in Figure 13. This curve also has the desired characteristic of greatest sensitivity at lowest flow rates.

CONCLUSIONS AND FURTHER PLANS

Satisfactory prototypes of three basic leak meters have been obtained. A sample of each is presently at Rocketdyne for testing in the very near future on the F-1 engine and later on the J-2.

Ten units of each of the Δp instruments and of the two versions of the heated thermocouple instrument are on order. All are scheduled for delivery in August 1962. A contractor for the hot wire instrument and its electronic assembly is being sought. Since it is the most advanced in development, more than ten units will be purchased; however, no estimate of the delivery date can be given at this time.

It is believed that these basic instruments can be modified to have increased sensitivity by a factor of 2 to 3. If instruments more sensitive by a factor of 10 are required, new basic types may be necessary.

Although these units are specifically tailored for lox leaks, they will operate without modification with any cryogenic liquid or any gas with temperature under about 100°C. Hot gas leaks will require provisions for preconditioning to 150°C or less. Fluid leaks will require extensive modification of these transducers.

APPENDIX A

DERIVATION OF Δp UNIT'S FORMULA

The following derivation is given in Trans-Sonics' project summary:

The flow of gas that we are interested in measuring is determined by the pressure drop developed across a fixed capillary tube. The general expression for flow through a capillary can be expressed by equation (1)*.

$$Q = \frac{P_1 V_1}{t\ T_1} = \frac{K_1 A^4}{\eta_T \ell T_1} P_a \ (P_2 - P_1) \tag{1}$$

where:

Q = volume-pressure per time = $\frac{PV}{t}$ at a temperature of T_1

t = time

A = cross sectional area of the tube

ℓ = length of the tube

P_a = average pressure across the capillary = $1/2(P_1 + P_2)$ in mmHg

P_2 = pressure at the inlet of the tube in mmHg

P_1 = pressure at the outlet of the tube in mmHg

η_T = coefficient of viscosity at the temperature T_1

$$\eta_T = \eta \left(\frac{T_1}{T_s}\right)^{.7}$$

T_1 = measured temperature in °K.

For a fixed length of capillary tube and where the absolute pressure and temperature are variables, we have:

$$Q = K_3 \Delta P_1 \ (2P_1 + \Delta p) \left(\frac{T_s}{T_1}\right)^{.7} \tag{2}$$

where T_s = is a standard temperature of 298°K and $\Delta P = P_1 - P_2$.

Converting Q to standard cubic centimeters per minute:

Q_s = volume per time at standard pressure of 760 mmHg (P_s) and standard temperature of 298 K° (T_s)

$$Q_s = K_3 \ x \left(\frac{P_1}{P_s} + \frac{xP_x}{2P_s}\right) \left(\frac{T_s}{T_1}\right)^{1.7} \tag{3}$$

where x = fraction of full scale pressure and P_x is the full scale pressure of 30 mmHg.

*Dushman, Vacuum Technique, Chapter 2, John Wiley & Sons, Inc., New York, N.Y.

The full scale flow rate can be written as

$$Q_s' = 976\left(\frac{P_1}{P_s} + .024\right)\left(\frac{T_s}{T_1}\right)^{1.7} \tag{4}$$

Equation (4) is the full scale flow as a function of the capillary outlet pressure (P_1) and the capillary temperature (T_1) in terms of standard cubic centimeters per minute.

Referring to equation (3), it is seen that flow rate as a function of the pressure drop across the capillary yields a curve that is almost linear. However, errors because of end effects and curvature of the capillary tube cause approximately -13% deviation from a straight line through the end points.

Temperature effects shown in this section are theoretical and not exactly true because of effects of the heaters and some unknown factor. The actual errors are much less than predicted. It appears that a more accurate expression for flow through the leak detector would be

$$Q_s = 976\left(\frac{P_1}{P_s} + .024\right)\left(\frac{T_s}{T_1}\right)^{.72}$$

This expression will yield data accurate to within ±5%.

APPENDIX B

SELECTION OF UNITS

In 1960, M-ASTR-I proposed that leak rates be expressed in cubic centimeters per minute (cc/min)[6]. Two of the instruments are basically mass flow measurement devices, however. It was planned to express their calibration in terms of milligrams O_2 per minute. There are 1.429 milligrams of O_2 in each standard cubic centimeter of gas. Table 1 lists some other conversion factors.

Recently, the Director of MSFC issued a policy statement on measuring units within MSFC[7]. This policy includes certain limitations and is presently only recommended to MSFC contractors. The policy establishes the metric gravitational system as the standard.

The volume flow rate units of cc/min. are uneffected by the new policy. However, use of the gravitational system implies that the basic mass unit will be the kilopond sec^2 per meter — the metric equivalent of the English slug. Thus, mass flow rate would be in units of kilopond sec per meter or a multiple or fraction of this. Until a standard unit has been defined, it is suggested that mg/min. continue to be used.

TABLE 1

To Convert:	To:	Multiply by:
Std. cc	mg O_2	1.429
Std. $ft.^3$	mg O_2	40465
Lb	mg	453592
Mg O_2	std. cc	.6998
Std. $ft.^3$	std. cc	28317
Lb O_2	std. cc	5291
Mg O_2	std. $ft.^3$	.00002471
Std. cc	std. $ft.^3$	.00003531
Lb O_2	std. $ft.^3$	11.21
Mg	lb	.000002205
Std. cc	lb O_2	.000189
Std. $ft.^3$	lb O_2	.08921
Std. cc	mg air	1.293
Std. cc	mg N_2	1.251
Std. cc	mg He	.1785
Std. cc	mg H_2	.08988
Mg air	std. cc	.7734
Mg N_2	std. cc	.7994
Mg He	std. cc	5.602
Mg H_2	std. cc	11.13

APPENDIX C

MISCELLANEOUS DATA

Tables 2 and 3 are included for use in calculations involving the heated element transducers; .05 gm-mole/min. is used because it is about the same magnitude as the maximum leak expected.

TABLE 2

Gas	Molecular Weight	mg/min. of .05 gm-mole/min.	std. cc/min. of .05 gm-mole/min.
O_2	32.000	1,601	1,120
Air*	28.966	1,449	1,120
N_2	28.016	1,402	1,120
He	4.003	200.2	1,120
H_2	2.016	100.8	1,120

*Dry Air: .7809 moles/mole N_2
.2095 moles/mole O_2
.0093 moles/mole A
.0003 moles/mole CO_2

TABLE 3

Molar Heat Capacity at Constant Pressure at 298.16°K		
O_2	7.02	calories/deg. C/gm-formular-weight
H_2	6.89	calories/deg. C/gm-formular-weight
N_2	6.23	calories/deg. C/gm-formular-weight
He	4.97	calories/deg. C/gm-formular-weight

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APPROVAL M-ASTR-IN-62-14

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M-P&VE
Mr. Paul (5)
Mr. Belew (3)
Mr. Bergeler (2)

M-TEST
Mr. Heimburg
Mr. Driscoll
Dr. Sieber (2)

M-ASTR
Dr. Haeussermann/Ref. File
Mr. Hoberg
Mr. Kampmeier
Mr. Burke
Mr. Smith
Mr. Paludan (50)
Miss Flowers

M-MS-IP